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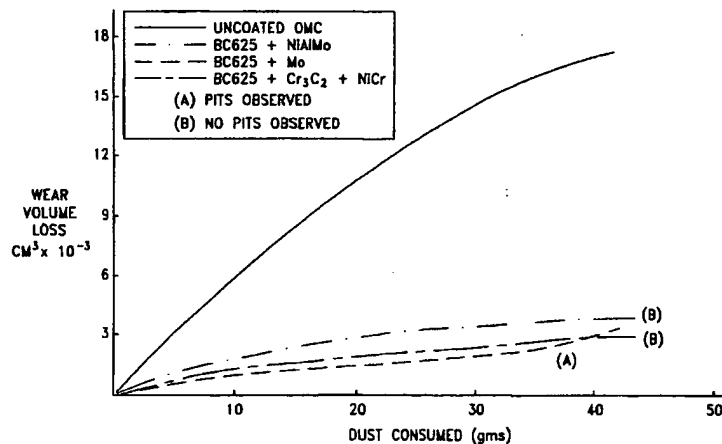
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(54) Title: EROSION-RESISTANT COATINGS FOR ORGANIC MATRIC COMPOSITES



(57) Abstract: This invention is directed to a coated article having an erosion-resistant coating and a method of providing the erosion-resistant coating to the article. The coated article has an increased useful lifespan and will resist erosion even in high-temperature environments. The coated article includes an organic resin substrate, a high-temperature erosion-resistant coating, and a bonding layer to secure the coating to the substrate. The bond coating can comprise a material selected from zinc, aluminum, aluminum-silicon alloy, chromium, titanium, nickel, silicon, tin, antimony, copper, iron, stainless steel, silver, and mixtures thereof. The erosion-resistant coating can be provided as a substantially non-porous layer comprising a material selected from the group of carbides, fluorides, nitrides, oxides and mixtures thereof of materials such as nickel, cobalt, iron, chromium, tungsten, and molybdenum. The organic resin substrate is prepared to receive the erosion-resistant coating by grip-blasting the resin surface. The metallic bond coat is then applied to the resin surface, and an erosion-resistant coating is deposited on the metallic bond coating.

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## EROSION-RESISTANT COATINGS FOR ORGANIC MATRIC COMPOSITES

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### BACKGROUND OF THE INVENTION

The present invention relates generally to coatings for organic matrix composite substrates, and more particularly to a method of providing a hard, adherent, erosion-resistant coating on the surface of an organic matrix composite.

There is continued demand from the aeronautical, aerospace and marine industries for lightweight, strong materials to replace heavy metal components. These lightweight components are often used in demanding and hostile environments such as in gas turbine engines to decrease weight, increase fuel efficiency and increase engine performance. For example, replacement of heavy metal blades and vanes in turbine engines provides more economical operation of these engines.

Synthetic organic resins have increasingly been used to manufacture strong, lightweight components. Since many of these resins can also withstand high operating temperatures, they are particularly useful for the construction of turbine engine components. Examples of commercially available high temperature resins include Epoxy, PMR 15, PMR 25, BMI, PEEU, PEEK and PAM.

Some of the most promising organic resins are organic matrix composites (OMC). These composites are organic resins that include reinforcing components encapsulated in the resin. The reinforcing components provide substantial mechanical strength to the resin. The reinforcing components can be formed as fibers, platelets, whiskers and particulates. Typical examples of materials that can be used as reinforcing components include carbon, glass, quartz, metal, metal oxides and ceramics.

Selected OMCs can provide the mechanical strength and thermal stability necessary to replace many heavier metal components in turbine engines; however, components formed with the OMCs are frequently short lived because they wear excessively in the hostile environments in which they are used. Often components are

exposed to severe abrasive forces, for example, impaction by sand, rain, hailstones and other particulates entrained in high velocity wind streams. These particles can quickly erode the relatively soft OMC components. The eroded components must be replaced frequently to maintain the performance requirements of many turbines.

- 5 Otherwise a severely eroded turbine component can disintegrate in use causing potential engine failure.

Application of a hard coating to a shaped organic matrix resin could provide an erosion-resistant component useful for gas turbine engines. However, coating organic resins with a hard metallic or ceramic coating presents unique problems. For  
10 example, the coating must be applied to the resin without jeopardizing the shape and structural integrity of a shaped resin. Also, the hard coating must bond and remain bonded to the resin surface. Further, the coating should have good compatibility with the organic resin to minimize stress and, therefore, prevent delamination when the coated component heats up or cools down. Moreover, the coating should not separate  
15 from the resin when the component is subjected to abrasive materials or struck with larger particles. In addition, the coating should be sufficiently thin and lightweight to minimize weight, yet sufficiently hard to provide adequate protection. The prior art has not successfully developed such coatings.

A need therefore exists for thin, lightweight, erosion-resistant coatings for  
20 organic matrix composites that may be used in high-temperature environments. The present invention addresses that need.

### SUMMARY OF THE INVENTION

Briefly describing one aspect of the present invention, there is provided a coated article that is lightweight, has an increased usable life span and resists erosion even in high temperature environments. The coated article comprises an organic resin substrate (preferably an organic matrix resin substrate), a high-temperature, erosion-resistant coating, and a bonding layer to secure the coating to the substrate.

The erosion-resistant coating is provided as a substantially non-porous layer and comprises a material selected from the group consisting of carbide, boride, nitride, oxide and mixtures thereof. The non-porous layer additionally can comprise materials such as nickel, cobalt, iron, chromium, tungsten, molybdenum, polyester and nylon.

The organic resin substrate comprises a polymers selected from the group consisting of polyimide, poly(phenyl sulfide), polybenzoxazole, polycarbonate, polyepoxide, polyphthalamide, polyketone, and mixtures of these polymers. Reinforcing materials such as glass, carbon, quartz, kevlar, metal, metal oxide, ceramic, etc., may be included in the organic resin substrate.

The bonding layer preferably comprises zinc, aluminum, silicon, zinc-aluminum, aluminum-silicon, and zinc-silicon compositions, although other materials such as tin, antimony, copper, chromium, titanium, or nickel may also be used alone or in combination with those mentioned above.

The method of providing the erosion resistant coating comprises preparing the organic resin surface, applying a metallic bond coating and depositing the erosion-resistant coating to the organic resin. The organic resin can be prepared by grit blasting the resin surface with an abrasive material such as aluminum oxide ( $\text{Al}_2\text{O}_3$ ), silicon carbide ( $\text{SiC}$ ), and the like. Preferably, the coatings are applied while maintaining the temperature of the resin below about 500 °F.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a graph comparing the amount of mass lost from an organic matrix composite to the amount of dust (sand) consumed.

### DETAILED DESCRIPTION OF THE INVENTION

For the purposes of promoting an understanding of the principles of the present invention, reference will now be made to preferred embodiments, and specific language will be used to describe the same. It will nevertheless be understood that no limitation of the scope of the invention is intended thereby. Any alterations and further modification in the described processes, systems or devices, and any further applications of the principles of the invention as described herein are contemplated as would normally occur to one skilled in the art to which the invention relates.

As briefly described above, the present invention relates to new erosion-resistant coatings for organic resin substrates. A bond coating layer is preferably used to fix the coating to the substrate. The coatings are useful for making strong yet lightweight composite materials for use in high temperature operating environments.

The organic resin substrate can be made from a wide variety of thermally stable resins, such as polyimides, polysulfides, polycarbonates, polyepoxides, polyphthalamides, polyketones, etc. Mixtures of organic resin materials may also be used.

The preferred organic resins are sufficiently thermally stable to withstand common techniques used for coatings, such as thermal spray, plating, overlay or CVD. Preferably the resin has an operating temperature above about 300 °F, more preferably about 400 °F and most preferably above about 500 °F. (For the purposes of this disclosure, the operating temperature is a minimum temperature that the resin can withstand without significant deformation or loss in structural strength.)

The heat deflection temperature (HDT) and the glass transition temperature (Tg) of a resin are two parameters that can be used to determine whether a resin is suitable for the present invention. A resin's HDT can be measured using standard test ASTM D 648-97 "Standard Test Method for Deflection Temperature of Plastics Under Flexural Load." Organic resins that have an HDT greater than about 300 °F more preferably greater than about 500 °F are suitable for use in this invention. The Tg of a

resin can be measured according to ASTM E 1640-94 "Standard Test Method for Assignment of the Glass Transition Temperature by Dynamic Mechanical Analysis."

Specific examples of high temperature resins useful in this invention include polyimide, (bismaleimide), poly(phenyl sulfide), polybenzoxazole, polycarbonate, 5 polyepoxide, polyphthalamide, polyketones, and mixtures of these polymers. Many of these high temperature polymers are readily commercially available. Polyimides such as PMR 15 , PMR 25 and BMI can be obtained from Quantum Composites. A polyphthalamide resin is sold under the trade name AMODEL® by Amoco. A polyketone resin sold under the trade name PEEK.

10 In certain preferred embodiments, the organic resin contains a reinforcing component. The reinforcing component imparts sufficient mechanical strength to the resin for use as structural components such as blades or vanes in gas turbine engines. Reinforcing components such as fibers, platelets, whiskers, and particulates are commonly embedded in resins to provide organic matrix composites. Most 15 commonly used reinforcing components are fibers. The fibers can be chopped fibers, continuous fibers, oriented fibers, woven or nonwoven fibers. Examples of specific materials that can compose the reinforcing components include: carbon, glass, quartz, kevlar, metal, metal oxide and ceramic.

In the most preferred embodiments the organic matrix composite comprises a 20 polymer designated as PMR 15, or a polymer designated as PMR 25. These resins include a polyimide resin and contain carbon fibers designated as T650-35 chopped carbon fibers embedded therein. The resin designated as PMR 15 has an operating temperature of about 475° to about 525°F. The resin designated as PMR 25 has an operating temperature of about 500 °F to about 600 °F. Other high temperature resins 25 available to the industry can also be used as a substrate in this invention.

Turning now to the erosion-resistant coating, which is deposited on the substrate, the erosion-resistant coating provides the organic matrix with an outer, wear-resistant surface that protects the substrate from harsh environments and increases the longevity of the coated substrate. In some applications the erosion-



resistant coating is "over coated" with another coating material such as a polymer, wax. Polyurethane, paint, etc., to improve the erosion-resistant properties.

The erosion-resistant coating for this invention includes materials selected from nickel, chromium, cobalt, iron, tungsten, molybdenum, and carbides, borides, nitrides, oxide intermetallics of various metals such as tungsten, aluminum, chromium, nickel, silicon, titanium, zirconium, and boron, and mixtures of these materials – either as stoichiometric components or as composites. Specific examples of materials that are suitable for use in the coating include, but are not limited to: Cr, Mo, BW, Co, Ni, NiCr, WC, Cr<sub>3</sub>C<sub>2</sub>, Al<sub>2</sub>C<sub>3</sub>, TiB<sub>2</sub>, HfC, CrB<sub>2</sub>, SiC, B<sub>4</sub>C, CrN, CBN, TiN, TiAlN, ZrN, CrO<sub>2</sub>, SiO<sub>2</sub>, diamond films, diamond-like carbon structures, and mixtures of these materials.

Preferably, the erosion-resistant coating is deposited on the bond coating to provide a top coating as a monolithic coating. The top coat preferably has a thickness of about 0.1 to about 4 mils.

To provide the most effective erosion-resistant surface, the erosion-resistant coating is provided as a substantially non-porous, non-columnar coating. Preferably, the erosion-resistant coating has a density greater than about 95%, more preferably greater than about 98%, most preferably greater than about 99%. The uninterrupted surface structure of a non-porous coating provides a more uniform surface that exhibits less tendency to delaminate under abrasive conditions than a columnar-type coating. Some degree of porosity is present in all coatings; generally, the pores result from air gaps between the metal particles, which compose the coating. Typically, thermally sprayed coatings according to this invention have a density of about 80% to about 99%. This substantially non-porous surface resists pitting and chipping, even when exposed to high-energy impingement from hard particulates such as sand.

As indicated above, the erosion-resistant coating is secured to the substrate using a bond coating layer. The bond coating preferably includes a metal such as, for example, zinc, aluminum, aluminum-silicon, chromium, titanium, nickel, silicon, tin, antimony, copper, iron (including stainless steel), silver and mixtures of these metals. Zinc and aluminum-silicon compositions are most preferred.

Most preferably, the bond coating layer is in direct contact with both the organic resin and the erosion-resistant coating. Thus, the bond coating provides an adhesive layer between the resin and the erosion-resistant coating. The bond coating also provides significant advantages to inhibit debonding from the resin. Debonding is most often exhibited as spallation or delamination where one or more of the coatings separate from the substrate.

The bond coating can be formed as a single layer or multiple layers of the above-mentioned metals or mixtures of these metals. When the bond coating is provided as multiple layers, each layer need not contain the same metal or mixtures of metals. A coated system comprising a multiple layer bond coating can be used when necessary to increase the compatibility between the resin and the hard erosion-resistant coating. Application of multiple layers of either the same metal or different metals can decrease the stress created in the coated system as the different materials expand and contract by varying amounts and at different rates upon heating or cooling. Preferably, the bond coating is formed as a single layer having a coating thickness of about 0.2 mil to about 3 mils.

The present invention also provides methods for adhering the hard, erosion-resistant coatings onto the organic resins using a bond coating. To apply the adherent coatings, the organic resin surface must be properly prepared. Preferably, the organic resin is abrasively blasted to provide a surface with the proper texture for adhering to the bond coating. The bond coating is then deposited at processing temperatures below about 500 °F using common deposition techniques, such as thermal spray, plating, overlay and chemical vapor deposition processes. The erosion-resistant coating also is applied using processing temperatures below about 500 °F. Typical application processes for the erosion-resistant coating include plasma spray, high velocity oxy/fuel (HVOF), argon shroud plasma spray, sputtering, chemical vapor deposition and cathodic arc-PVD.

The resulting coated substrate exhibits enhanced erosion resistance when exposed to abrasive environments. Furthermore, the coated substrate resists spallation

and delamination when subjected to repeated thermal cycling between ambient temperatures and about 500 °F.

The erosion-resistant coating is formed by first preparing the surface of the organic resin to receive the bond coating. After the resin surface has been prepared  
5 the bond coating is applied. Thereafter the hard, erosion-resistant coating is deposited on the bond coating.

The surface of the organic resin must be prepared to provide good adhesion to the bond coating. For optimum adhesion, it is important that the surface be textured to provide mechanical interlock with the bond coating, yet the surface must be  
10 sufficiently smooth so that scratches, grooves, or furrows are not visible. The resin surface can be prepared by a variety of techniques such as, for example, sanding, abrasive blasting, and chemical methods. Abrasives that can be used with this invention include abrasives commonly known and used in the art. Typically aluminum oxide and silicon carbide abrasives are used.

15 Preferably, the organic resin is prepared by abrasively blasting its surface using aluminum oxide ( $\text{Al}_2\text{O}_3$ ) having an average particle size of about 45 to about 65 mesh, more preferably, about 50 to about 60 mesh. Use of aluminum oxide having a larger median particle size removes too much of the resin surface, in effect, eroding or wearing away the resin surface. Furthermore, use of large particles gouge the resin  
20 surface, plowing deep scratches into the surface, which can compromise the structural integrity of the coated substrate. Use of aluminum oxide having smaller median particle size does not sufficiently roughen the resin surface to adhere to the bond coating. The resin surface must be sufficient rough or coarse to produce a textured surface than can provide a mechanical interlock with the bond coating. The resin  
25 material must be carefully grit blasted to produce a "keyed" surface or, irregular surface profile for the sprayed droplets to adhere.

The resin's surface can be abrasively blasted using a variety of commercial grit blast spray equipment. A suction gun (model 32850 by Dayton) operating at a pressure of about 15 to 25 psi provides sufficient force to abrasively prepare the resin  
30 surface without gouging or eroding away the resin surface. Alternatively, direct

pressure spray guns (such as models sold by Empire) also can be used. However, since the direct pressure gun propels particles at approximately three times the velocity as a suction gun operated at the same pressure, the pressure for direct pressure gun must be controlled accordingly.

5           The bond coating can be applied by a variety of techniques commonly used in the art. Examples of application techniques useful for the present invention include: thermal spray, plating, overlay and chemical vapor deposition. The bond coating is applied by maintaining the organic resin at a processing temperature below the resin's deformation temperature. Preferably the organic resin is maintained at a temperature  
10 below about 500 °F, more preferably below about 400 °F, most preferably below about 350 °F. The temperature of the resin can be controlled by blowing compressed air (or other non-reactive gas) over the backside of the resin surface as the coating is applied. Auxiliary cooling jets, which direct forced air toward the resin surface and are attached to or adjacent to the thermal spray gun, can be used simultaneously with  
15 the spray gun. In addition or alternatively to the auxiliary cooling jets, the bond coating can be applied by randomly or uniformly interrupting the application process. The short interruptions to allow the resin to cool down. After a short interruption, the coating application is continued until a bond coating having the desired thickness is formed on the resin surface.

20           For resins that deform at temperatures within about 15 °F to about 20 °F of the processing temperature, a backing plate temporarily can be added to the surface of the resin opposite the side to be coated. The backing plate provides support for the hot resin and maintains the substrate's shape. If more than one side of the resin is coated, the backing plate can be removed or transferred to a different position on the resin  
25 surface. In addition, multiple backing plates, each backing plate having a different shape that conforms to a portion of the shaped resin's surface, can be used in this invention.

          In a preferred embodiment, the bond coating is applied using a thermal or wire spray technique. This technique provides a coating composed of individual metal or  
30 metal containing particles. The particles mechanically interlock with each other to

form a solid, dense coating. This dense coating adheres primarily through a mechanical anchoring with the roughened resin surface. The bond coating is supplied to provide a coating thickness that can vary from about 0.2 mm to about 3 mm. Preferably, a single bond coating is applied; however, if desired, multiple bond coatings can be applied. If multiple bond coatings are applied, each bond coating should have a thickness of about 0.2 mm to about 1.0 mm.

The erosion-resistant coating is deposited onto the bond coating. The erosion-resistant coating can be applied using a variety of techniques, which include thermal spray, plating, overlay, chemical vapor deposition, plasma spray, high velocity oxy/fuel, argon shroud plasma spray, sputtering and cathodic arc-PVD. Preferably, a single layer erosion-resistant coating is deposited. However, if desired, multiple coatings can be deposited. The erosion-resistant coating is deposited to have a coating thickness of between about 0.1 mil and about 4 mils. As with the application of the bond coating, the process temperature for deposition of the erosion-resistant coating is maintained below about 500 °F, more preferably below about 400 °F, most preferably below about 350 °F. The resin temperature can be controlled as described above for the application of the bond coating.

Deposition of the erosion-resistant coating using the methods described above provides a non-porous top coating that is both non-columnar and columnar. Typically, the overlay (sputter, cathodic arc, PVD, etc.) and CVD processes deposit columnar structures while the spray and plating processes deposit equiaxed or non-columnar structures.

Moreover, the erosion-resistant coating has a much higher density than cast or wrought alloys because it is substantially nonporous. For instance, the top coating applied according to the present invention provides a coating having a density of about 95%, more preferably about 98% and still more preferably 99%. This provides a top coating having a porosity less than about 5%, more preferably less than about 2%, and still more preferably less than or equal to about 0.1%.

The coated substrates prepared according to the present invention exhibit significantly greater longevity. The adhesion of the coating to the substrate is very

good – as demonstrated by the thermal cycling evaluations described below. The abrasion resistance is also excellent – as demonstrated by abrasive impingement testing.

Reference will now be made to specific examples using the preferred materials and methods described above. It is to be understood that the examples are provided to more completely describe preferred embodiments, and that no limitation to the scope of the invention is intended thereby.

### EXAMPLE 1

#### Preparation of Adherent Tungsten Carbide-Cobalt Coatings

A coupon having a surface area 1" x 3" and .100" thick of an organic matrix composite comprising a polyimide sold under the trade name PMR-15 was mixed with chipped carbon fibers by sheet molding technique and was cleaned by first wiping the resin surface with an appropriate organic solvent, then abrasively blasting the surface with 54 mesh  $Al_2O_3$  using a suction spray gun operating at a pressure of about 15 to 25 psi. The resulting organic composite surface was textured.

The resin coupon was positioned on top of a backing plate of steel. A zinc bond coating was applied using a Sulzer Metco 10E wire gun with a 2AF flow meter. Zinc wire (0.125") was applied to the organic composite surface at a spray distance of 5" to provide a zinc coating thickness of 0.002" to 0.003". The coating was applied in successive passes without stopping. Cooling air was applied to the back surface.

A top coating of tungsten carbide and cobalt was applied using a Sulzer Metco 7M plasma spray system with 4MP powder feeder. The application temperature was maintained below about 500 °F. The resulting top coating had a thickness of about 0.002" to about 0.003".

A series of coated coupons were prepared as described above. Specific examples of the coupons and the coatings are listed in Table. 1.

TABLE 1

| Bond Coating<br>(Thickness,<br>mils) | Application<br>Method | Erosion-<br>Resistant<br>Coating     | Application<br>Method |
|--------------------------------------|-----------------------|--------------------------------------|-----------------------|
| Zinc<br>(2 - 3)                      | Combustion<br>Flame   | WC-Co                                | Plasma Spray          |
| Zinc<br>(2 - 3)                      | Combustion<br>Flame   | Cr <sub>3</sub> C <sub>2</sub> -NiCr | Plasma Spray          |
| Zinc<br>(2 - 3)                      | Combustion<br>Flame   | CrO <sub>2</sub>                     | Plasma Spray          |
| Zinc<br>(2 - 3)                      | Combustion<br>Flame   | CrO <sub>2</sub> -SiO <sub>2</sub>   | Plasma Spray          |

5

**EXAMPLE 2****Thermal Shock Cycling**

Prior to erosion testing, thermal shock tests were performed to verify coating adherence. Generally, poorly bonded coatings will tend to exhibit coating spall. All coated specimens were subjected to repeated shock cycling. The coated  
 10 substrates were heated at a rate of about 50 °F/ minute until they reached 500 °F, then held for one hour, then the hot, coated substrates were cooled to ambient temperature by fan cooling. This heating/cooling cycle was repeated at least ten times.

Evaluation of the resulting substrates under the ten-fold magnification  
 15 revealed no evidence of spallation or delamination of the bond or hard coating from the surface. This indicated that the bond coats (e.g., Zn, Al-Si, stainless steel composite with polyester, etc.) and topcoats (e.g., WC-Co, Cr<sub>3</sub>C<sub>2</sub> - NiCr, MoAlNi) were compatible with the OMC substrate and yielded good adhesion. It is to be noted that the broad range of bond coat compositions and top coat compositions  
 20 indicated in this invention also provides an erosion resistant coating system which is compatible with the OMC substrate.

**EXAMPLE 3****Sand Impingement Tests**

After verifying the good adhesion of the erosion resistant coating systems through thermal shock tests, the coated specimens were then subjected to abrasive (sand) impingement tests. It is to be noted that in the erosion tests, the hard top coatings play the primary role of providing erosion resistance. In a similar manner, the bond coatings play the primary role in improving adhesion of hard coating to the OMC substrate in the aforementioned thermal shock tests.

Table 2 lists the results of abrasive impingement tests, which were conducted on the uncoated OMC Substrate No. 1, and Coated OMC Substrates Nos. 2 and 5, by blasting the substrate surface with Arizona Road Dust Sand having an average particle size between 30-50 microns at a 30°-impingement angle. The nozzle to specimen distance was maintained at 1.2 inches. The said abrasive was blasted at 80 psi for 60 minutes using a mass of about 40 grams of sand.

The results of the erosion tests indicate that the top coatings on Substrate Nos. 2-5 provided a significant improvement in erosion resistance (4-7.5x) when compared to the uncoated Substrate No. 1. It is to be understood that other hard coatings such as TiN, TiAlN, SiC, TiB<sub>2</sub>, diamond-like carbon, etc., will also provide similar benefits in improvement of the useful life span of a coated substrate.



**TABLE 2**  
**Summary of Erosion Test Results**

| Substrate No. | Substrate                     | Coating                  |                                       | Average Volume Loss cc | Average Relative Improvement in Erosion Resistance |
|---------------|-------------------------------|--------------------------|---------------------------------------|------------------------|--|
|               |                               | Bond Coat                | Top Coat                              |                        |  |
| 1             | PMR – 15/ Carbon Fibers (OMC) | No                       | No                                    | 0.0246                 | 1  |
| 2             | PMR – 15/ Carbon Fibers (OMC) | Zn, Al-Si, 5.5 Composite | WC-Co                                 | 0.0033                 | 7.45x  |
| 3             | PMR – 15/ Carbon Fibers (OMC) | Zn, Al-Si, 5.5 Composite | Cr <sub>3</sub> C <sub>2</sub> – NiCr | 0.0035                 | 7.02x  |
| 4             | PMR – 15/ Carbon Fibers (OMC) | Zn, Al-Si, 5.5 Composite | CrO <sub>2</sub>                      | 0.0056                 | 4.28x  |
| 5             | PMR – 15/ Carbon Fibers (OMC) | Zn, Al-Si, 5.5 Composite | MoAlNi                                | 0.0037                 | 6.65x  |

5

While the invention has been illustrated and described in detail in the foregoing description, the same is to be considered as illustrative and not restrictive in character, it being understood that only the preferred embodiment has been shown and described and that all changes and modifications that come within the spirit of the invention are desired to be protected.

10

**CLAIMS**

We claim:

1. A coated article comprising an organic resin substrate, a bond  
5 coating and an erosion-resistant coating, wherein said erosion-resistant coating is  
provided as a substantially non-porous layer comprising a material selected from  
the group consisting of nickel, cobalt, iron, chromium, tungsten, molybdenum,  
diamond, diamond-like carbon, polyester nylon, carbides, borides, nitrides, oxides,  
intermetallics, and mixtures thereof.  
10
2. The coated substrate of claim 1 wherein said non-porous layer  
comprises carbides, borides, nitrides, oxides and intermetallics of tungsten,  
aluminum, chromium, nickel, silicon titanium, zirconium boron, and mixtures of  
these materials.  
15
3. The coated substrate of claim 1 wherein the organic resin includes  
reinforcing material selected from the group consisting of carbon, glass, quartz,  
kevlar, metal, metal oxides, ceramics and mixtures thereof.
- 20 4. The coated substrate of claim 1 wherein the organic resin comprises  
a material selected from the group consisting of polyimides, poly(phenyl sulfide)s,  
polybenzoxazoles, polycarbonates, polyepoxides, polyphthalamides, and  
polyketones, and mixtures thereof.
- 25 5. The coated substrate of claim 1 wherein the bond coating has a  
coating thickness of about 0.2 to about 3 mils.

6. The coated substrate of claim 1 wherein the bond coating comprises a metal selected from the group consisting of zinc, aluminum, aluminum-silicon alloy, chromium, titanium, nickel, silicon, tin, antimony, copper, iron, stainless steel, silver, and mixtures thereof.

5

7. The coated substrate of claim 1 wherein the erosion-resistant coating is provided as a substantially non-porous layer comprising a material selected from the group consisting of Cr, Mo, W, Co, Ni, NiCr, WC-Co, Ni-B, Ni-SiC, MoAlNi, TiN-Mo, Cr<sub>3</sub>C<sub>2</sub>-NiCr, SiC, B<sub>4</sub>C, CrN, CBN, TiN, TiAlN, ZrN, 10 CrO<sub>2</sub>, SiO<sub>2</sub>, diamond films, diamond-like carbon and mixtures thereof.

8. The coated substrate of claim 1 wherein the erosion-resistant coating has a coating thickness of about 0.1 to about 4 mils.

15 9. The coated substrate of claim 1 wherein the erosion-resistant coating has a porosity of about 5 % to about 0.1%.

10 10. The coated substrate of claim 1 wherein the erosion-resistant coating has a porosity of about 2% to about 0.1%.

20

11. A method of providing an erosion-resistant coating to a surface of an organic resin, said method comprising:

preparing the surface of the organic resin;

applying a metallic bond coating to the organic resin; and

25 depositing a substantially non-columnar coating comprising a material selected from the group consisting of carbides, borides, nitrides, oxides and mixtures thereof to provide the erosion-resistant coating.

12. The method of claim 11 wherein the organic resin comprises a 30 polymer is selected from the group consisting of polyimide, poly(phenyl sulfide)

polybenzoxazole, polycarbonate, polyepoxide, polyphthalamide, polyketone, and mixtures thereof.

13. The method of claim 11 wherein the organic resin comprises a  
5 reinforcing material.

14. The method of claim 11 wherein preparing the surface of the organic resin includes blasting the surface with an abrasive material.

10 15. The method of claim 11 wherein the abrasive material used to prepare the surface includes  $\text{Al}_2\text{O}_3$  or SiC particles having an average particle size of about 45 to about 65 mesh.

15 16. The method of claim 15 wherein the abrasive material used to prepare the surface includes  $\text{Al}_2\text{O}_3$  or SiC particles having an average particle size of about 50 to about 60 mesh.

17. The method of claim 11 wherein preparing the surface of the organic resin includes abrasive cleaning the organic resin surface with an abrasive  
20 material at a pressure of about 15 to about 25 psig.

18. The method of claim 11 wherein the metallic bond coating includes a metal selected from the group consisting of zinc, aluminum, aluminum-silicon alloy, chromium, titanium, nickel, silicon, tin, antimony, copper, iron, stainless  
25 steel, silver, and mixtures thereof.

19. The method of claim 11 wherein applying a metallic bond coating consists of applying a single bond coating.

20. The method of claim 11 wherein the metallic bond coating has an average thickness of about 0.2 mils to about 3 mils.

21. The method of claim 11 wherein the metallic bond coating is  
5 applied using a thermal spray technique or wire spray process or plating or CVD process.

22. The method of claim 11 wherein applying the metallic bond coating includes maintaining the organic resin at a temperature below about 500 °F.

10

23. The method of claim 11 wherein the erosion-resistant coating has an average thickness of about 0.1 mil to about 4 mils.

24. The method of claim 11 wherein the erosion-resistant coating  
15 comprises a material selected from the group consisting essentially of Cr, Mo, W, Co, Ni, NiCr, WC-Co, Cr<sub>3</sub>C<sub>2</sub>-NiCr, SiC, B<sub>4</sub>C, CrN, SBN, TiN, TiAlN, ZrN, CrO<sub>2</sub>, SiO<sub>2</sub>, diamond films and mixtures thereof.

25. The method of claim 11 wherein the erosion-resistant coating has a  
20 porosity of less than about 5%.

26. The method of claim 25 wherein the erosion-resistant coating has a porosity of less than about 2%.

27. The method of claim 11 wherein deposition of the substantially non-  
25 columnar coating includes maintaining the organic resin at a temperature below about 500 °F.

28. The method of claim 11 wherein the erosion-resistant coating is deposited using a CVD, thermal spray, electroplating, electroless plating overlay or cathodic arc deposition technique.

5           29. A method of adhering an erosion-resistant coating to a surface of an organic resin, the method comprising:

                  abrasively blasting the surface of the organic resin with an abrasive material;

                  applying a bond coating to the surface of the organic resin; and  
10               depositing an erosion-resistant coating on the bond coating.

30. The method of claim 29 wherein the organic resin comprises a polymer selected from the group consisting of polyimides, poly(arylene sulfide)s, polybenzoxazoles, polycarbonates, polyepoxides, polyphthalamides, and  
15           polyketones, and mixtures thereof.

31. The method of claim 29 wherein the organic resin comprises a reinforcing material selected from the group consisting essentially of carbon, glass, quartz, kevlar, metal, metal oxides, and ceramics, and mixtures thereof.

20

32. The method of claim 29 wherein the abrasive material to includes a material selected from the group consisting of  $\text{Al}_2\text{O}_3$  and SiC, and mixtures thereof.

25           33. The method of claim 32 wherein the abrasive material has a median particle size of about 45 to about 65 mesh.

34. The method of claim 33 wherein the abrasive material has a median particle size of about 50 to about 60 mesh.

30

35. The method of claim 29 wherein the bond coating includes at least one metal selected from the group consisting of zinc, aluminum, aluminum-silicon alloy, chromium, titanium, nickel, silicon, tin, antimony, copper, iron, stainless steel, silver, and mixtures thereof.

5

36. The method of claim 29 wherein deposition of the erosion-resistant coating includes maintaining the organic resin at a temperature below about 500°F.

10

37. The method of claim 29 wherein the bond coating consists of a single layer.

38. The method of claim 29 wherein the bond coating has an average thickness of about 0.2 mils to about 3 mils.

15

39. The method of claim 29 wherein the bond coating is applied using a thermal spray technique.

40. The method of claim 29 wherein the erosion-resistant coating has an average thickness of about 0.1 mil to about 4 mils.

20

41. The method of claim 29 wherein the erosion-resistant coating comprises a material selected from the group consisting essentially of Cr, Mo, W, Co, Ni, NiCr, WC-Co, Cr<sub>3</sub>C<sub>2</sub>-NiCr, SiC, B<sub>4</sub>C, CrN, CBN, TiN, TiAlN, ZrN, CrO<sub>2</sub>, SiO<sub>2</sub>, diamond films, and diamond-like carbon, and mixtures thereof.

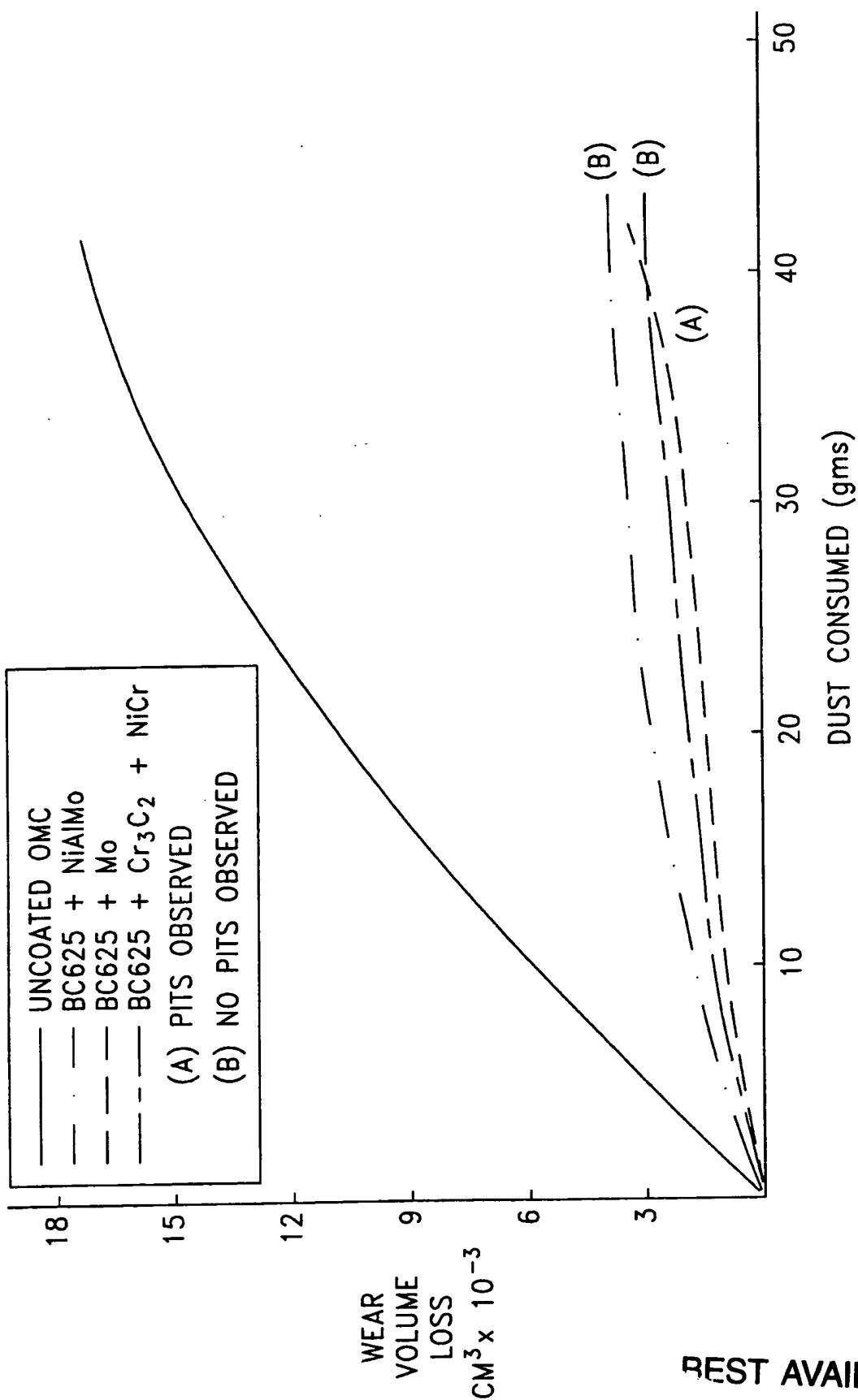
25

42. The method of claim 29 wherein the erosion-resistant coating is deposited at a process temperature below about 500 °F.

30

43. The method of claim 29 wherein the erosion-resistant coating is deposited using a CVD, thermal spray, electroplating, electroless plating overlay or HVOF technique.





**Fig. 1**